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Determination of heat generation by correlating the interfacial friction stress with temperature in friction stir welding

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ABSTRACT

A three-dimensional computational fluid dynamics (CFD) model is established to analyze the interfacial friction stress and the associated heat flux at the tool-workpiece interface in friction stir welding. A novel method is proposed to calculate the interfacial friction stress directly based on the yield criterion, without any need to determine the friction factor first. The interfacial friction stress is described as a function of temperature. The variations of interfacial friction stress, heat generation, temperature field, and material flow are numerically simulated. The predicted thermal cycle and geometry of thermo-mechanically affected zone are in good agreement with the experimentally measured ones.

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1. Introduction

During friction stir welding (FSW) process, the frictional stress at the tool-workpiece interface determines the heat generation, temperature profile and plastic deformation around the tool [1,2]. As plastic material flow, torque, and energy requirement are largely influenced by the nature of friction stress [3–5], therefore a proper and accurate estimation of friction stress is extremely vital for establishing an accurate and robust numerical model of FSW. Although a large amount of work has been reported to understand the frictional mechanisms involved in FSW process, estimation of interfacial friction stress along the interfaces still remains untouched because of the complex mechanism involved at the tool-workpiece interface. Moreover, how to exactly express a friction model in FSW is rather controversial up to now. Guerdoux [6] found that minor variation in friction parameters causes significant variation in the temperature profile and the welding force in FSW. Therefore, hypotheses or approximations often have to be made, and simple friction models may be good. In metal forming simulations, friction has been traditionally assumed to follow the Coulomb's or the Tresca (constant) friction law [7]. Both of them have also been used in various FSW models.

In the Coulomb's friction model, friction stress is proportional to the contact pressure,

$$\vec{\tau}_f = -\mu_f p \frac{\Delta\vec{v}}{\left\|\Delta\vec{v}\right\|} \tag{1}$$

where τ_f is the friction stress, μ_f is the coefficient of Coulomb's friction, p is the contact pressure, and Δv is the relative sliding velocity at the contact interface.

For modeling the FSW process, several researchers assumed that the interfacial friction could be characterized by the Coulomb's friction law, and the contact pressure was considered as a constant at the interface [8–19]. Therefore, the coefficient of Coulomb's friction becomes the crucial factor that determines the value of friction stress. However, the value of the coefficient of Coulomb's friction is affected by several factors, such as temperature, contact surface roughness, relative motion, applied force, and contact compliance (i.e., sliding or sticking friction conditions) etc. Frigaard et al. [12] reasoned that in case of steel tool and aluminum workpiece, the coefficient of Coulomb's friction can be taken in the range from 0.25 to 0.5, while 0.45 is proven to be the most appropriate value. Through the numerical modeling of FSW process, Soundararajan et al. [13] stated that the value of the coefficient of Coulomb's friction decreases gradually from 0.5 to 0.4 when the temperature increases at the contact interface. Zhang [14] took a constant value of the coefficient of friction equivalent to 0.3 in their numerical simulation. Hamilton et al. [15] chose the coefficient of friction according to the energy levels. The initial calculation of the energy used a coefficient of friction of 0.5. If energy levels exceeded

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2000 J/mm, the coefficient of friction was reduced to 0.45, and if the energy levels exceeded 3000 J/mm, the coefficient of friction was further reduced to 0.4. At the same time, the energies were recalculated according to the reassigned values of coefficient of friction. Assidi et al. [16] thought that 0.25 or 0.3 are the optimum values of coefficient of friction. It was observed that if μ_f= 0.25 the predicted and measured temperature matched well, while if μ_f= 0.3 the predicted and measured force was in good agreement. Chen et al. [17] performed CFD modeling of FSW with driving force boundary, and the coefficient of friction was taken as constant equal to 0.25. Su et al. [2] determined the average values of coefficient of friction and slip rate simultaneously by measuring tool torque and axial force. The results showed that the value of the coefficient of friction lies in the range of 0.095–0.502. Zhang et al. [18] used a temperature-dependent apparent coefficient of friction solved by the inverse solution method to estimate the heat generation rate, and established the relationship between the heat generation, friction coefficient, and temperature. Meyghani et al. [19] estimated the coefficient of friction varies within the range of 0.207089 to 0.000582 when the temperature changes from 25 °C to 580 °C for AA6061-T6.

In the Tresca (constant) friction model [20,21], friction stress is a fraction of the shear yield stress of the material,

$$\vec{\tau}_f = -m\tau_y \frac{\Delta\vec{v}}{\left\|\Delta\vec{v}\right\|} \tag{2}$$

where m is the friction factor which is limited between zero and one [20], and τ_y is the shear yield stress of the material that can be obtained according to the von Mises yield criterion.

The Tresca (constant) friction model is widely used in the plastic forming process where three-dimensional stress is remarkable, such as extrusion and upsetting with large deformation etc. [22,23]. In FSW process, the material under the shoulder is subjected to three-dimensional stress. Therefore, the Tresca (constant) friction model is suitable to describe the friction state at the interface between tool and workpiece. The shear yield stress can be calculated by the yield stress of the material based on von Mises yield criterion. Therefore, the friction factor is the key to determine the value of friction stress. Buffa et al. [24] proposed that when the average value of friction factor is 0.46 at the interface, the predicted temperature history agreed well with the measured one in FSW experiment. In linear friction welding of aluminum, Buffa et al. [25,26] obtained an average curve of the friction factor m, which increases with rising in temperature and changes from zero to one. Gao et al. [27] used the friction factor 0.6 to model the microstructure evolution during friction stir spot welding in AA6082-T6. Pal et al. [28] investigated the heat partition between tool and workpiece during FSW of SS304 using CFD modeling, and the friction factor was selected as 0.7. Jain et al. [29] developed a model to evaluate the performance of two different pin shapes in FSW process, and the friction factor was set as a constant 0.4.

Whether it is the coefficient of friction in Coulomb's friction model or the friction factor in Tresca (constant) friction model, both of them are difficult to be measured or calculated because they are multivariable dependent quantities. So far, their values (coefficient of friction and friction factor) are determined according to the past experience or adjusted based on the comparison between simulation and experimental results, thus lacking of theoretical basis.

In this study, a novel method is proposed to calculate the interfacial friction stress directly based on the yield criterion, without any need to determine the friction factor first. The interfacial friction stress is described as a function of temperature. A three-dimensional CFD model is established to predict the behavior of interfacial friction stress and heat flux at tool-workpiece interface.

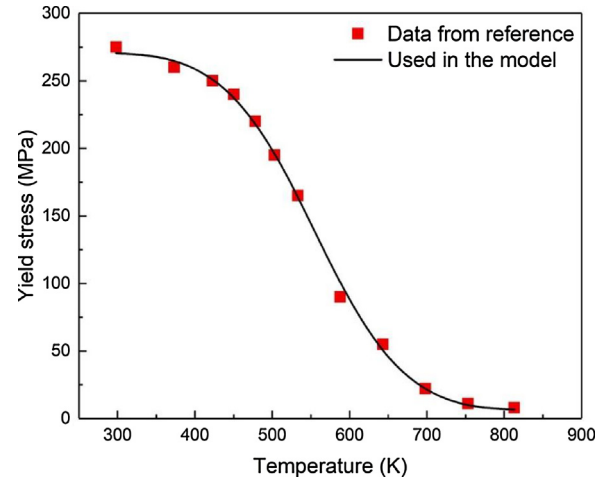

Fig. 1. Temperature-dependent yield stress of AA6061-T6 [42].

The variations of interfacial friction stress, heat generation, temperature field, and material flow are checked out through numerical simulation. The simulation results are verified by measuring real-time temperature profile as well as the TMAZ boundary.

2. Stress analysis at the interface

The contact stresses acting on the tool-workpiece interface drive the material flow in FSW. The magnitude and nature of the contact stresses are dependent on the contact states at the interface. In order to identify the contact states between tool and workpiece, the slip rate (δ) is introduced [30],

$$\delta = \frac{\omega_T - \omega_M}{\omega_T} = 0.31 \times \exp\left(\frac{\omega \cdot r}{1.87}\right) - 0.026 \tag{3}$$

where ω_T and ω_M are the angular velocities of the tool and the material adjacent to the tool, respectively, ω is the tool rotation speed, and r is the radial distance away from the tool axis.

When the contact state is of sliding type (δ = 1), there is no movement of the material ($\omega_M = 0$), thereby the contact stress (τ_c) can be considered as equal to the friction stress (τ_f). When the contact state is of sticking type (δ = 0), the velocity of the material adjacent to tool-workpiece interface is equal to that of tool ($\omega_M = \omega_T$), and the contact stress is equal to the shear yield strength (τ_y) of the workpiece material. When the contact state is of partial sliding/sticking type ($0 < \delta < 1$), the contact stress at the tool-workpiece interface is given by,

$$\tau_c = \left(1 - \delta\right)\tau_y + \delta\tau_f \tag{4}$$

where τ_y is the shear yield strength of the material, and τ_f is the interfacial friction stress.

The contact stress can be used to determine the heat generation at the tool-workpiece interface,

$$q_s = \left[\eta_s \cdot \left(1 - \delta\right)\tau_y + \delta\tau_f\right] \cdot |v_T| \tag{5}$$

where q_s is the heat generation rate at the interface, η_s is the fraction of plastic deformation work dissipated in the form of heat, and v_T is the tool rotation velocity.

In Eq. (5), the shear yield stress τ_y can be calculated according to the von-Mises yield criterion,

$$\tau_y = \sigma/\sqrt{3} \tag{6}$$

where σ is the yield stress of the material. It can be obtained according to the data published [42], which is shown in Fig. 1. If only the interfacial friction stress τ_f is known, is the heat generation rate q_s at the interface determined.

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